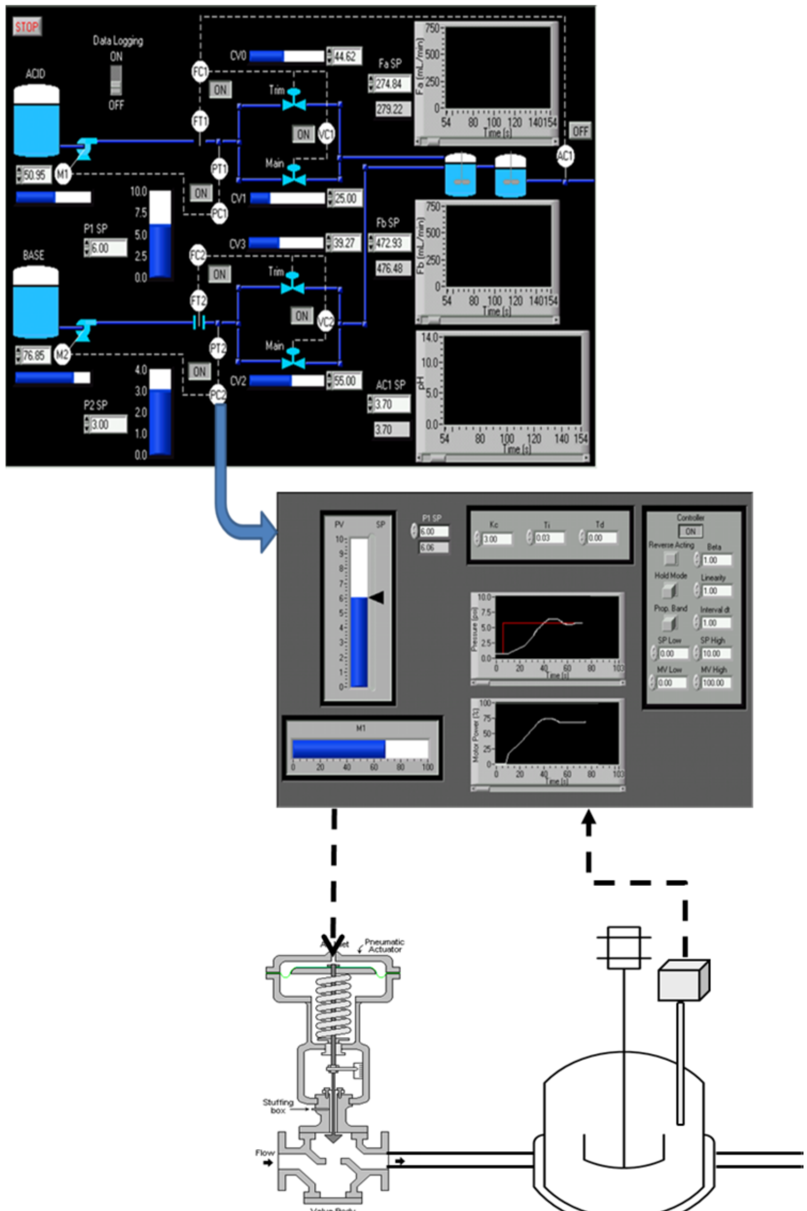
Operability in Process Design

Appendix A: Process Control Equipment



Valve from Beychok (2012)

Thomas Marlin

Process Control Equipment release 2.0 on November 2012

This material is provided to promote education in the general field of "process operability" via the Internet site www.pc-education.mcmaster.ca . It is an appendix for an integrated presentation of selected operability topics.

The author would like to hear from readers on how they are using this material. In addition, he would appreciate suggestions for improvements and extensions. He can be contacted at marlint@mcmaster.ca .

Acknowledgement

- Peggy Hewitt for assisting in obtaining a control room picture.
- Everyone who posts materials with the Creative Commons license

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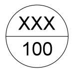
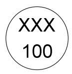
Symbols



CONTROL ROOM BOARD MOUNTED INSTRUMENT

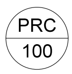


LOCAL BOARD MOUNTED INSTRUMENT

MEASURED VARIABLE:
L: LEVEL
P: PRESSURE
A: ANALYZER
F: FLOW
T: TEMPERATURE

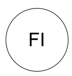
FUNCTIONS:
I: INDICATOR
C: CONTROLLER
A: ALARM
(H =HIGH, L=LOW)

EXAMPLES:

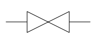


PRESSURE RECORDER CONTROLLER: I.D. NUMBER 100, MOUNTED IN CENTRAL CONTROL ROOM.

TAH TEMPERATURE ALARM: ACTIVATED AT HIGH TEMPERATURE.



LOCAL FLOW INDICATOR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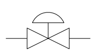
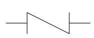
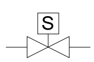
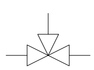

DIAPHRAGM VALVE: CONTROLLED BY AIR LINE

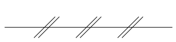

CHECK (ONE-WAY) VALVE



SOLENOID VALVE CONTROLLED BY ELECTRICAL SIGNAL

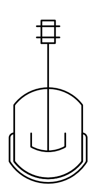

THREE-WAY VALVE


SPRING LOADED SAFETY VALVE


AIR LINE

ELECTRICAL SIGNAL

ELECTRICAL (CURRENT) TO PNEUMATIC SIGNAL CONVERTER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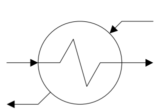
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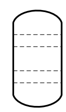
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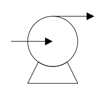
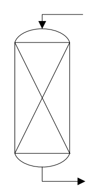
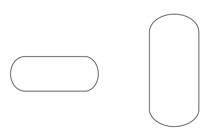

CENTRIFUGAL PUMP


PACKED TOWER OR PROCESS VESSEL (SUCH AS A REACTOR).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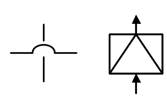
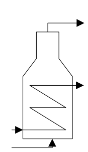
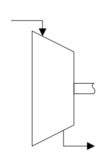

RUPTURE DISK, BURST DIAPHRAGM


FIRED HEATER (FURNACE)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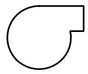
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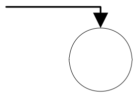
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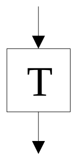
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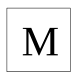
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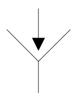
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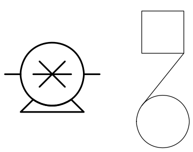
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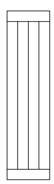
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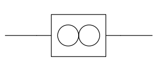
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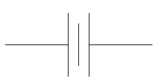
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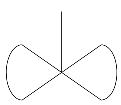
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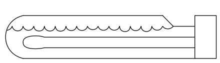
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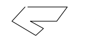
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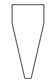
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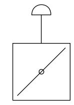
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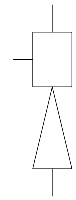
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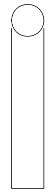
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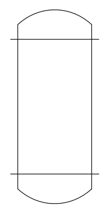
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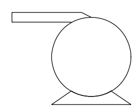
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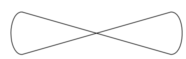
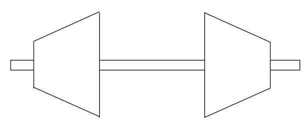

FAN


TURBINE USED TO PROVIDE WORK TO DRIVE COMPRESSOR

Nomenclature

CSTR	Continuous (flow) stirred tank reactor
HAZOP	Hazard and Operability Study
LOPA	Layer of Protective Analysis
P&ID	Piping and instrumentation drawing
PID	Proportional-integral-derivative controller

Appendix A. Process Control Equipment

A.0 To the Student

Process control is essential for achieving desired process operations safely and reliably as disturbances occur in the plant. While engineers and operators understand the needed actions, only precise automation through process control can implement actions as fast and reliably as required in demanding chemical processes. In fact, the entire development of the technology of automatic control has been in response to demands for controlling steam engines, airplanes, electronic circuits, chemical plants, and many other complex systems.

This material emphasizes equipment used to implement process control that is essential for all topics in operability. Naturally, the equipment presented material here complements Chapter 6 on process control principles, algorithms and design; naturally, because the designs will be implemented with equipment described in this appendix. In addition, control equipment performance is important for safety, reliability and troubleshooting; therefore, the material is separated from the control chapter and presented in this appendix.

Control equipment technology is developing rapidly, so the presentation here can only present an overview of the equipment currently in use, and it makes no attempt to look into the future develops that will likely occur rapidly. Perhaps more importantly, the basic principles defined in tables of important attributes of the basic elements, sensors, final elements, and signal transmission, will guide your future learning in this topic.

This information is essential for engineers designing plant, managing operations, and operating pilot plants and laboratories. So, let’s learn some more about the equipment that enables automation!

A.1 Basics of Process Control

Why is process control necessary in a chemical process? Some reasons are given in the following; can you think of others?

- Plants are physically large, so that adjustments and data collection must be managed from centralized locations
- Materials can be hazardous and maintained at extreme conditions, e.g., high pressures and temperatures
- Equipment functions successfully without damage over only a limited range of conditions, so that excursions outside of acceptable ranges must be avoided
- Demands for product quality and safety require rapid and precise process adjustments that are often beyond the capability of plant personnel
- People must be relieved of high frequency actions that can be automated so that they can perform more complex, low frequency analyses that are better performed by people

Process control involves a large and continuously expanding array of technology. Here, we will address the technology that is implemented in a typical process control design. This technology is based on one basic principle, feedback.

Feedback uses information in system outputs for deciding adjustments to system inputs.

The use of system outputs requires measurements of process variables that are influenced or caused by adjustable variables. The selection of output variables for measurement is critical to success and will be addressed throughout the chapter. Input variables can be adjusted by a person or computer; for example, a valve opening is an acceptable input variable, while the feed temperature is not (unless it can be influenced by an adjustable variable like a valve affecting steam to a feed heat exchanger).

The schematic in Figure A.1 shows a feedback control loop with limited detail, containing the essential three elements of sensor, control calculation and final element. The loop requires inputs from plant personnel in the form of controller tuning constants and the set point, giving the desired value for the variable. Then, the controller functions essentially continuously by adjusting the valve to bring the controlled variable to its set point. However, process control does not result in a plant running on "automatic pilot". Since control systems involve complex equipment that can fail to operate properly, plant personnel monitor their performance and intervene when a fault has been diagnosed.

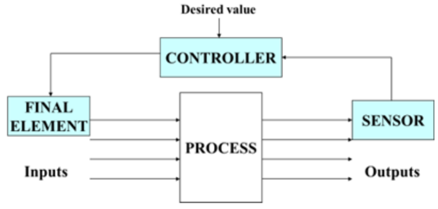


Figure A.1 Schematic of Feedback control loop

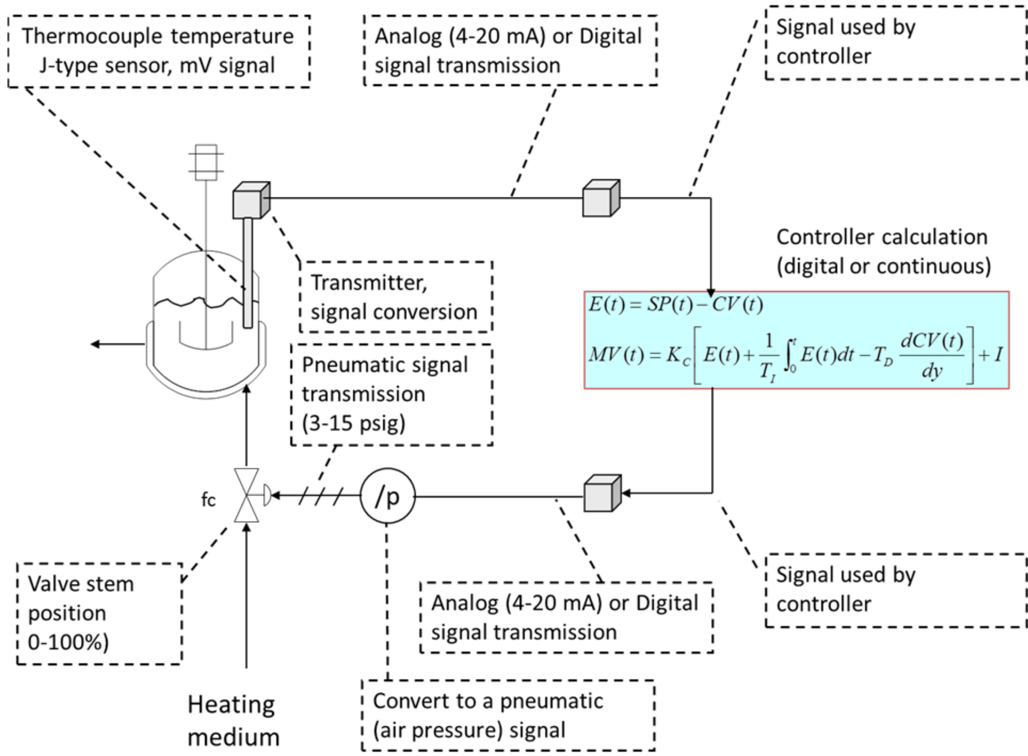


Figure A.2. Typical equipment for a single-loop controller, with human-machine interface not shown. Note that signal transmission and control calculation control equipment can be based on analog (shown here) or digital technology.

Figure A.1 pictures the concepts of control, but engineers need to design equipment to realize these concepts. Let's begin with a single control loop to determine the key equipment common to all controllers shown in Figure A.2. The sensor generates a signal that is proportional to the measured variable; in the example, a thermocouple produces a millivolt signal that is (approximately) proportional to the temperature. The signal is converted in a transmitter to an alternative signal that can be accurately transmitted longer distances and is compatible with other equipment in the loop; the transmitted signal would typically be an analog current or a digital signal. The transmitted signal is converted for use in the calculation equipment; this could be voltage for analog equipment or a decimal number for digital control. In addition to the controller calculation, the measurement signal is used for display and historical storage and can be used for calculations. The calculated result is converted for transmission to the final element. The transmitted signal is converted to affect the final element near the final element. In many process applications, the final element is a control valve, and the signal must determine the force provided by compressed air. Thus, the transmitted signal is converted to an air pressure. The pneumatic signal is applied to the final element that changes its stem position and opening for flow. Every control loop in a plant has its own individual local equipment, sensor, pneumatic converter, and final element. The control calculation and transmission can use individual equipment or can use digital equipment that could be shared among a number of control loops.

Figure A.3 Picture of a typical centralized control room. (Photo courtesy of Worsley Alumina)

A large segment (or the entirety) of a process plant is controlled in a centralized location, where a few people can observe all measurements and make adjustments throughout the plant. The centralized control house enables coordinated actions, but it requires long transmission. Fortunately, the current electronic and digital signals can be transmitted with essentially no delay. A picture of a typical centralized control room is shown in Figure A.3.

All sensors must be located at the process equipment, while displays of the measurement can be located either at the equipment or centrally, or both. Local displays of measurements are essential for plant personnel who are performing maintenance and are monitoring the equipment. For example, when an operator starts a pump, s/he wants to observe the outlet pressure and perhaps, the flow as well, to ensure that the equipment is working properly. However, coordinated analysis and control of the entire plant requires that most measurements be transmitted and displayed in the centralized control room. Most of these will be recorded on trend plots to provide a display of the recent dynamic behavior. When appropriate, a measurement can be displayed both locally and remotely.

Modern control equipment in the centralized facility includes a network of computers. The network has the following advantages (over a single, centralized computer).

- Parallel computation ensures minimal computing delay in control loops.
- The behavior for a failure is superior. Even though the probability of failures is higher, because of the increased equipment, the impact of a failure is much lower since only a small section of the plant is affected.

To further improve reliability, most digital equipment is redundant with automatic switching upon failure detection.

- Computer software and hardware can be tailored in each module for specific functions, like process control, complex and flexible computations, history storage and display, safety functions, and so forth.
- The computing system can be designed to match a plant, without excess capacity, while allowing subsequent modular expansion.

It is important to recognize that control systems have many preprogrammed functions, so that plant engineers do not program PID control algorithms, details of graphical displays, and so forth. Most control systems require “configuring” calculations, displays and history storage using existing functions.

We conclude this section with a brief discussion of drawings that are used to document designs. We have to recognize that complex designs could not be documented using written descriptions. Drawings are widely used as a basis for construction, and there are many forms of drawings, including Block Flow, Mechanical Detail, Piping and Instrumentation Drawing (P&ID), and Isometric (3-D) Layout. A clear explanation of process drawings is provided with examples by Turton et al (2003). Here, we will concentrate on the P&ID, whose major characteristics are given in Table A.1. The P&IDs are used during day-to-day operation and for safety studies; therefore, the P&ID must be maintained up-to-date as changes are made to the original design and construction.

Table A.1. Typical features of Piping and Instrumentation Drawings (P&ID)*

P&ID contain the following	**P&ID does not contain the following**
• All piping and equipment connections	• The distance between objects. The drawing is not to scale.
• An approximate location for connections (e.g., top or bottom of tank, tray location, etc.)	• The vertical or horizontal (or 3D) position of objects
• Equipment identification (numbers)	• The sizes of objects(e.g., vessel), not even the relative size
• The size of piping	• The exact design for piping connections, including those to vessels
• All sensors (whether locally or remotely displayed and recorded) and whether used for an alarm, with priority	• Sensor details such as physical principle (e.g., thermocouple) and measurement range
• All valves (whether automated for remote operation or not), including failure position if remotely operated valves	• Details of the control calculations when involving complex logic and/or calculations
• Control strategies, as much detail as possible graphically. These can be regulatory and safety related	• Any detail about the human interface display or the type of historical data
• Whether signals and control calculations are implemented using analog or digital equipment	• Operating policy (which appears in a separate operations manual)

* Various levels of detail are presented in a P&ID, depending on the status of the design (preliminary to definitive) and company practices.

Various levels of detail are presented in a P&ID. Limited information is available during the preliminary design of the process, so that the P&ID does not include as much detail concerning the sensors and control implementation. The drawings in this educational material will tend to follow the preliminary P&ID level of detail. Preparing P&IDs is facilitated by special-purpose software that includes a library of process-related symbols. Perhaps the best, low-cost software for use by university students is MS Visio™ (Microsoft, 2012).

Prior to addressing control technology, we need to build a basic understanding of two topics. The next section addresses some key issues with sensors and final elements, transmission, and calculation. Then, the next section addresses the impact of the process design on the ability to control key variables; naturally, the chemical engineer must find a balance between process and control design that achieves the desired performance. Subsequent sections present control design for simple and more complex process systems.

A.2 Sensors

Sensors are selected to match process needs. Naturally, sensors are critical for control; we can apply feedback control to only variables that we can measure. In addition, many sensors are essential for process monitoring by plant personnel so that they can identify incipient problems and diagnose abnormal situations. In fact, most process plants have four to five monitoring sensors for every sensor used for control. Issues important for selecting a sensor are the same whether it is used for control or monitoring, although the emphasis changes depending on the application. Table A.2 presents the most important issues.

Table A.2 Key Issues in selecting a sensor.

Issue		Comment
• **Accuracy -** Accuracy is the degree of conformity of the measured value with the accepted standard or ideal value, which we can take as the true physical variable. Accuracy is usually reported as a range of maximum inaccuracy. These ranges should have a significance level, such as 95% of the measurements will be within the accuracy range. Good accuracy is needed for some variables, such as product quality, but it is not required for others such as level in a large storage tank.		Accuracy is usually expressed in engineering units or as a percentage of the sensor range. Unfortunately, the statistical meaning of the reported values is seldom supplied. It is best to assume that these ranges are 95% confidence ranges.
• **Repeatability** – The closeness of agreement among a number of consecutive measurements of the same variable (value) under the same operating conditions, approaching in the same direction.		The term “approaching in the same direction” means that the variable is increasing (decreasing) to the value for all replications of the experiment.

• **Reproducibility** – The closeness of agreement among a number of consecutive measurements of the same variable (value) under the same operating conditions over a period of time, approaching from both directions. This is usually expressed as non-reproducibility as a percentage of range (span). Often, an important balance is between accuracy and reproducibility, with the proper choice depending on each process application.		The period of time is "long", so that changes occurring over longer times of plant operation are included. Reproducibility includes hysteresis, dead band, drift and repeatability.
• **Range/Span** - Most sensors have a limited range over which a process variable can be measured, defined by the lower and upper range values. Usually, the range is larger, the accuracy and reproducibility are poorer. Therefore, engineers select the smallest range that satisfies the process requirements. We select ranges that are easily interpreted by operating personnel, such as 100-200 °C, but not 100-183 °C.		If a chemical reactor typically operates at 300 °C, the engineer might select a range of 250-350 °C. Since the reactor will be started up from ambient temperature occasionally, an additional sensor should be provided with a range of -50 to 400 °C.
• **Reliability** – Reliability is the probability that a device will adequately perform (as specified) for a period of time under specified operating conditions. Some sensors are required for safety or product quality, and therefore, they should be very reliable. Reliability is affected by maintenance and consistency with process environment (see topic below).		If sensor reliability is very important, the engineer can provide duplicate sensors, so that a single failure does not require a process shutdown.
• **Linearity -** This is the closeness to a straight line of the relationship between the true process variable and the measurement. Lack of linearity does not necessarily degrade sensor performance. If the nonlinearity can be modeled and an appropriate correction applied to the measurement before it is used for monitoring and control, the effect of the non-linearity can be eliminated. Typical examples of compensating calculations are the square root applied to the orifice flow sensor and the polynomial compensation for a thermocouple temperature sensor. The engineer should not assume that a compensation for non-linearity has been applied, especially when taking values from a history database, which does not contain details of the measurement technology.		Linearity is usually reported as non-linearity, which is the maximum of the deviation between the calibration curve and a straight line positioned so that the maximum deviation is minimized. See ISA (1979) for further details and several alternative definitions of linearity.
• **Maintenance** - Sensors require occasional testing and replacement of selected components that can wear. Engineers must know the maintenance requirements so that they can provide adequate spare parts and personnel time. Naturally, the maintenance costs must be included in the economic analysis of a design.		On-stream analyzers usually require the greatest amount of maintenance. The cost associated with maintenance can be substantial and should not be overlooked in the economic analysis.

• **Consistency with process environment** - Most sensors will function properly for specific process conditions. For example, many flow sensors function for a single phase, but not for multi-phase fluid flow, whether vapor-liquid or slurry. The engineer must observe the limitations for each sensor. Some sensors can have direct contact with the process materials, while others must be protected. Three general categories are given in the following. • **Direct contact** - Sensors such as orifice plates and level floats have direct contact with process fluids. • **Sheath protection** - Sensors such as thermocouples and pressure diaphragms have a sheath between the process fluid and the sensor element. • **Sample extraction** - When the process environment is very hostile or the sensor is delicate and performs complex physiochemical process on the process material, a sample can be extracted.		A float can indicate the interface for a liquid level. However, a float is not reliable for a "sticky" liquid. Also, a flow turbine meter can be damaged by a rapid change in flow rate or liquid entrained in a vapor stream. Sensors in direct contact must not be degraded by the process material. The sheath usually slows the sensor response. The extracted material must be representative of the material in the process.
• **Dynamics** - The use of the sensor dictates the allowable delay in the sensor response. When the measured value is used for control, sensor delays should be minimized, while sensors used for monitoring longer-term trends can have some delay.		A greater delay is associated with sensors that require a sample to be extracted from the process. On-stream analyzers usually have the longest delays, which are caused by the time for analysis.
• **Safety -** The sensor and transmitter often require electrical power and might generate heat, either of which could provide a point for explosion of flammable gases.		Standards for safety have been developed to prevent explosions. These standards prevent a significant power source and flammable gas from being in contact.
• **Cost** - Engineers must always consider cost when making design and operations decisions. Sensors involve costs and when selected properly, provide benefits. These must be quantified and a profitability analysis performed. In some cases, a sensor can affect the operating costs of the process. An example is a flow sensor. In some situations, the pumping (or compression) costs can be high, and the pressure drop occurring because of the sensor can significantly increase the pumping costs. In such situations, a flow sensor with a low (non-recoverable) pressure drop is selected.		Remember that the total cost includes purchase, costs of transmission (wiring around the plant), installation, documentation, plant operations, and maintenance over the life of the sensor. See a reference on engineering economics to learn how to consider costs over time, using principles of the time value of money and profitability measures.
• **Failure behavior –** The sensor signal upon failure can be determined based on the physics of the sensor. This behavior is important for safety, reliability and troubleshooting.		For example, a likely thermocouple failure involves a wire break. Upon this failure, the millivolt signal will be zero, and the sensor will report a low value. The engineer must determine whether a control system receiving the low value will take an unsafe action.

Once we understand the issues, we can evaluate the performance of various candidate sensors against process requirements. An excellent source of information is available on the Internet that gives an introduction to commonly used process sensors and links to additional information on a wide array of sensors (Marlin, 2012); this portal provides introductory information and links to many internet resources. Additional, vendor-independent information is available in engineering handbooks, such as Liptak (1999 and 2003). Once you understand the general capabilities of sensor technology, you can access information provided by the manufacturer for further details. Surprisingly poor test results for industrial sensors are reported by Cornish (1995); sensors failed to meet vendor performance specifications when tested under ideal conditions. Therefore, the engineer would be wise to use published standard performance where vendor-supplied specifications promise far better performance.

Certainly, one of the most important sensor performance requires is for accuracy. Typical accuracy ranges for common sensors are reported in Table A.3 based on information in Liptak (2003). These are accuracies expected with new equipment operating under ideal assumptions. For example, the orifice flow sensor assumes the fluid density is known. Unless the fluid density is truly unchanging in the process or the measurement is corrected using a real-time density measurement (which is possible at additional cost), the experienced accuracy will be poorer than the value reported in the table. Clearly, engineers designing and operating manufacturing processes need to thoroughly understand the sensor principles and typical operating conditions, not just average conditions but their ranges.

Now, let's look at some examples of sensor selection.

Example A.1 Temperature sensor: We are measuring the temperature at the exit of a packed bed reactor in the range of 160-180 °C. We will control this temperature to influence the conversion in the reactor, and no real-time measure of outlet composition is available. What temperature sensor is recommended?

Temperature has a strong effect on reaction rate, so we need a sensor with very good accuracy. Repeatability is not adequate; we do not want to operate consistently at the wrong temperature. We want to be at (or very near) the correct temperature! Checking the performance of typical temperature sensors in Liptak (2003), we find the following information.

Sensor	***accuracy(°C)***	***maximum range(°C)***
Thermocouple (J)	***±1.0-2.8***	***0 to 750***
Resistance (RTD)	***±0.03-0.60***	***-200 to 650***
Thermistor	***±0.006-0.60***	***-40 to 150***

We will select an RTD that combines good accuracy, superior linearity and physical ruggedness. The thermistor is less rugged.

Table A.3 Typical Sensor Accuracy (Based on Liptak, 2003)

Sensor principle	Accuracy	Comments
FLOW		
Magnetic flow meter	1% of flow measurement	
Coriolis	0.2% of flow rate	
Orifice meter measuring pressure difference	1-2% of flow rate	Accuracy much poorer when flow less than 1/3 or span
Pitot	1-5% span	Very low non-recoverable pressure drop
Positive displacement	0.5-1% span	
LEVEL		
Pressure difference	0.5% span	Greater inaccuracy if density changes
Displacement	0.50% span	Greater inaccuracy if density changes
Float	1% span	(± 1 inch for level switch)
Radar	1-3 mm for tanks	Advantage is non-contact with fluid
TEMPERATURE		
Bimetallic		
Pyrometer	0.1-0.2% of value	Interference can lead to larger errors
RTD (Resistance)	Larger of 0.3 °C or 0.2% of span	
Thermocouple	1-2.8 °C	
Thermister	0.06-0.6 °C	
PRESSURE		
Bourdon and helical	0.25-5% span	Usually for local display
Strain gauge	0.1 -0.5 % span	
Capacitance	0.1 % span	
Piezoelectric	1 % span	

Example A.2 Sensor range: Typically, sensor accuracy and reproducibility degrade as the measurement range (span) is increased. Therefore, we prefer small ranges that measure over the expected range of variability. We are selecting a temperature sensor for a fired heater controller with an outlet temperature of 320 °C. The temperature fluctuates ± 5°C during normal operation, fluctuates ± 25°C during disturbances, and varies from ambient (0°C) to normal operation during startup and shutdown. What is the sensor range that you will define?

We would like to measure the normal operating temperature with good accuracy, but the range must include typical disturbances. We do not want to "fly blind", especially during a disturbance. Therefore, we would select a range of 270-370°C. How is the temperature measured during startup? We would install a second sensor with a range of 0-400 °C for use during startup.

Example A.3 Sensor location: We desire to control the heat transfer at the outlet of a shell and tube heat exchanger. A colleague proposes the design in Figure A.4a. Please provide your critique. (Almost all engineering work is reviewed by another engineer, so commenting on another person's work is not unusual, but we had better be diplomatic, because all of our work will be reviewed as well!)

A principle of feedback control is that a causal relationship must exist between the manipulated variable and the controlled variable. (We cannot steer an automobile by adjusting the headlights.) In the proposed design, changing the heating valve opening, and thus, the flow rate of heating fluid, does not influence the measured temperature. In fact, the sensor location measures the inlet temperature, while we desire to measure the outlet temperature. Therefore, we modify the design as shown in Figure A.4b.

Example A.4 Process conditions: We want to measure the flow rate of a gas at 3 MPa within ± 5%. The pressure of the gas at the sensor location varies from 2.5 to 3.5 MPa. Can we use an orifice meter for this application?

The typical orifice meter provides accuracy within ±1-3%. This looks OK for the application. However, the measurement depends on the stream conditions, as we learned in fluid mechanics. Therefore, the reported accuracy is only valid for specified, constant conditions! How does the pressure affect the accuracy? Let's look at the relationship between the measured pressure difference across an orifice and the actual flow rate, which was derived using the famous Bernoulli principle.

$$F = C_0 \sqrt{\frac{\Delta P}{\rho}} \qquad \text{(A.1)}$$

with
F = volumetric flow rate
C_0 = meter constant
ΔP = pressure difference across orifice
ρ = fluid density at stream conditions

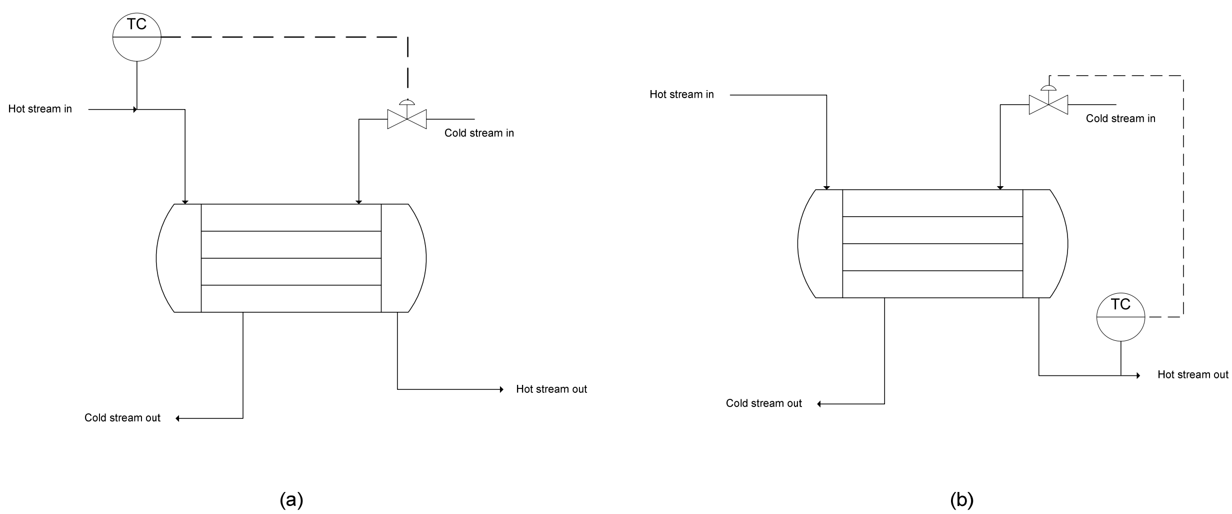


Figure A.4 Heat exchanger with sensor, controller and valve. (a) Original proposal and (b) Corrected design.

The pressure influences the fluid density. Assuming an ideal gas at these low pressures, the density is proportional to pressure. We will represent P_s as the variable stream pressure and P_d as the design value for pressure (3 MPa) used to determine the meter constant. The correct value of the volumetric flow rate can be determined as given below.

Calculation using the uncorrected meter equation, i.e., using design conditions

$$F = C_0\sqrt{\frac{\Delta P}{\rho_s}} = C_0\sqrt{\frac{\Delta P}{\rho_d}}\sqrt{\frac{\rho_d}{\rho_s}} = C_0\sqrt{\frac{\Delta P}{\rho_d}}\sqrt{\frac{P_d}{P_s}} = \beta\sqrt{\frac{\Delta P}{P_s}}$$

Correction factor for the stream pressure

All of the constant terms can be grouped into one parameter, β. We see that the correction term, not implemented in the original design, can be as large as $(3.0/2.5)^{0.5}$ or a factor of 1.095. Therefore, a measurement error of 9.5% can be caused by the change in stream pressure when the correction is not made. We conclude that the original design would not provide the required accuracy. To achieve the required accuracy, the stream pressure should be measured and used to correct the orifice pressure as shown in Figure A.5.

Proper sensor selection and location is critical for the success of process monitoring and control. It is recommended that you base your design choices on the issues in Table A.2. What if we cannot measure the key process controlled variable in real-time? This often occurs for product quality variables that can be measured periodically in a laboratory but are difficult to measure frequently using on-stream analysis. Well, all is not completely lost; we can apply the concept of inferential control that uses surrogate measured variables to infer the unmeasured variable. Inferential control is explained in section A.4.4 of this appendix.

A.3 Control valves

Naturally, final elements are critical for control; we cannot control what we cannot influence. In process control, most final elements are valves. In addition to valves for control, many valves are essential for isolating equipment for maintenance, for allowing flows to/from equipment during specific operations, and during emergency situations. Four major categories of valves are presented in Table A.4. In most process plants, the number of control valves in much smaller than the other three types of valves. Here, we will emphasize control valves.

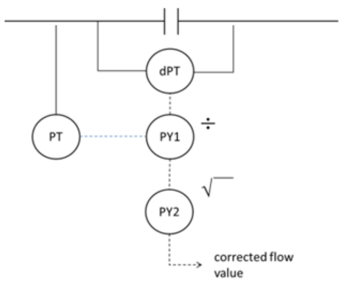
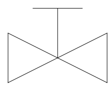
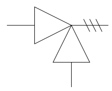
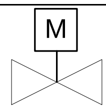
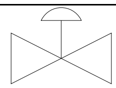


Figure A.5. Pressure-corrected orifice flow measurement. (PY symbol designates a general calculation, with the specific function indicated outside of the bubble.)

Table A.4 Major categories of valves in process plants.

Name	Symbol	Power	Typical process application
Block		Manual (by person)	These valves are usually fully opened or closed, although they can be used to regulate flow over short periods with a person adjusting the valve opening.
Safety Relief		Self-actuated (the difference between process and external pressures results in opening when appropriate)	These are located where a high (low) pressure in a closed process vessel or pipe could lead to an explosion (implosion).
On-off (open-closed)		Electric motor	These valves are normally used for isolating process equipment by ensuring that flows are not possible. They can be operated by a person in a centralized control room, who can respond quickly regardless of the distance to the valve.
Throttling control		Usually pneumatic pressure	These valves are typically used for process control, where the desired flow rate is attained by changing the opening of the valve.

A unique feature of a control valve is the ability to adjust its opening remotely using a signal determined by a person or a control computer. In most process plants, the signal is compressed air that provides sufficient force to adjust the stem position via the actuator. A sample control valve is shown in Figure A.6.

Issues important for selecting a control valve are presented in Table A.5. Once we understand the issues, we need to investigate the performance of various candidate valves. An excellent resource is available on the Internet that gives an introduction to commonly used valves and citations to additional information on a wide array of valves topics (Marlin, 2011). Additional, vendor-independent information is available in engineering handbooks, such as Liptak (1999). Once you understand the general capabilities of a valve technology, you can access information provided by manufacturers for further details.

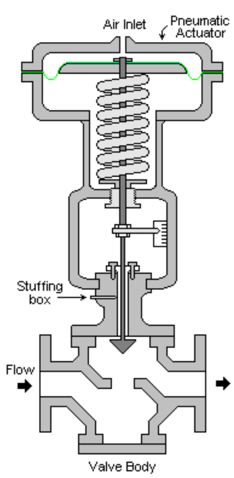


Figure A.6 Typical control valve.
(Beychok, 2012)

Table A.5. Key Issues in selecting control valves

Issue		Comments
• **Capacity** - The maximum flow rate through the flow system (pipes, valves, and process equipment) must meet operating requirements. Guidelines are available for calculating the pipe diameter for a desired flow rate, and guidelines are given here for the percentage of the system pressure drop contributed by the valve.		The driving force for flow, i.e., the pressure must be provided by a centrifugal pump or static pressure difference between vessels.
• **Range** - The range indicates the extent of flow values that the valve can reliably regulate; very small and large flows cannot be maintained at desired values.		This is often reported as a ratio of the largest to the smallest flows that can be controlled acceptably and is usually in the range of 35 to 50.
• **Safety/Failure position -** Each valve has a power supply that is used to move the valve to its desired opening. The most common power source is air pressure, but hydraulic pressure or an electric motor can be used. The power can be lost for one of two reasons (1) failure in the power source (e.g., air compressor) or (2) a failure of the controller equipment or signal transmission to the valve. The engineer must define whether the safest condition for each valve is fully open or fully closed. This will be the failure position, and the combination of the actuator and valve body must achieve this position upon loss of power.		We must analyze the entire process, including integrated units to identify the safest conditions. In a few cases, the failure condition is "unchanged". If the air power is lost, air leakage will result in a slow drift to either open or closed.
• Gain **-** The gain is $$K_p = \frac{\Delta \text{ measured variable}}{\Delta \text{ valve opening}}$$ In the equation, the measured variable refers to the variable being controlled by the valve adjustments. The gain should not be too small (or the variable cannot be influenced strongly enough as disturbances occur) or too large (which would require very small, precise changes to the valve opening).		Usually, the measured variable is expressed as a percentage of the normal range (or sensor range). If a sensor had a range of 0-200 °C, a five-degree change would be 2.5%. A typical range for the gain is 1 to 3 (dimensionless).
• **Pressure drop** - The purpose of the valve is to create a variable pressure drop in the flow system. However, a large pressure drop wastes energy. In some systems, the energy costs for pumping or compressing can be very high, and the pressure drop introduced by the valve should be as small as practically possible.		Here, the key factor is the non-recoverable pressure drop.

• **Precision** - Ideally, the valve would move to exactly the position indicated by the signal to the valve, which is usually a controller output. However, the valve is a real physical device that does not perform ideally. The following factors prevent ideal performance. • **Deadband** - Upon reversal of direction, the greatest amount that the signal to the valve can be changed without a change to the valve opening (stem position). • **Resolution -** The smallest amount that the signal to the valve can be changed without a change to the valve opening (stem position). This change is after a change that has overcome deadband and is in the same direction.		Two major causes of non-ideal valve behavior are backlash and stiction. **Backlash** - A relative movement between interacting parts, resulting from looseness, when motion is reversed. **Stiction** - Resistance to the start of motion usually required to overcome static friction. The valve precision can be improved by the addition of a *valve positioner*.
• **Linearity -** The relationship between the signal to the valve (or stem position) and the flow can be linear or non-linear. Either may be desired, since a linear relationship is sought between the signal to the valve and the measured variable (which is not necessarily the flow; it could be a pressure, temperature or other process measurement).		See the discussion on *valve characteristic* in Section 3.3 and in Marlin (2000), Chapter 16.
• **Dynamics** - The valve is part of the feedback system, and any delay due to the valve slows the feedback correction and degrades control performance. Therefore, the valve should achieve the desired opening rapidly.		The actuator must provide sufficient force and the speed of response can be improved by a *booster*. See Section 3.5.
• **Consistency with process environment** - Each valve body will function for specified fluid properties. Conditions requiring special consideration include slurries, very viscous fluids, flashing and cavitation. In addition, some applications require a tight shutoff. Naturally, the parts of the valve that contact the process must be selected appropriately to resist corrosion or other deleterious effects. In some processes, hygiene and toxicology require that all equipment be thoroughly flushed and cleaned periodically. The body should not allow collection of material that cannot be removed during cleaning.		**Flashing -** The pressure drop across the valve can result is partial vaporization of a liquid; this situation is termed flashing when the fluid after the valve remains at least partially vaporized. **Cavitation -** While the fluid at the entrance and exit of a control valve may be liquid, two phases may exist where the flow area in most narrow and the pressure is at its minimum. The situation leading to vaporization and subsequent condensation is termed cavitation and can cause *severe damage* to the valve.
• **Cost** - Engineers must always consider cost when making design and operations decisions. Valves involve costs and when selected properly, provide benefits. These must be quantified and a profitability analysis performed. In some cases, a valve can affect the operating costs of the process, where the pumping (or compression) costs can be high, and the pressure drop occurring because of the valve can significantly increase the pumping costs. In such situations, a valve with a low (non-recoverable) pressure drop is selected.		Remember that the total cost includes costs of transmission (wiring around the plant), installation, documentation, plant operations, and maintenance over the life of the valve. See a reference on engineering economics to learn how to consider costs over time, using principles of the time value of money and profitability measures.

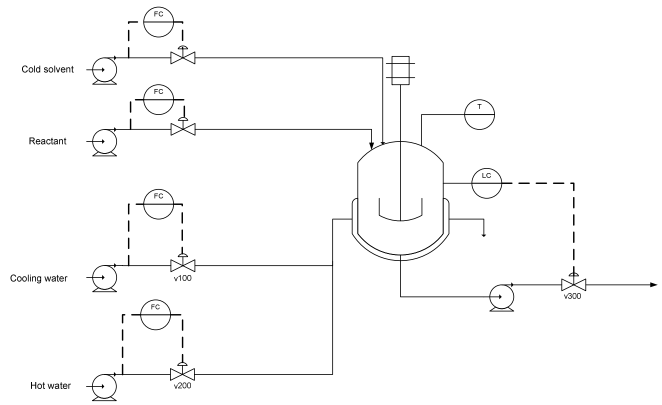


Figure A.7 Stirred tank reactor with cooling and heating.

Example A.5. Failure position: The air power to the control valve could fail due to causes such as a compressor stoppage, control computer or calculation error, or a fault in the signal transmission. When the failure occurs, the air pressure to the valve actuator becomes atmospheric, so that no force opposes the spring and the direction of the spring force determines the valve stem/plug position upon failure. We need to determine the failure position for control valves v100 and v200 in the process in Figure A.7. For each valve, decide whether the position for the valve stem/plug should be fully opened or closed.

Process safety is the major issue when selecting valve failure position. In this process, we want to prevent a high temperature in the reactor.

- ***v100 provides cooling to a closed chemical reactor; its failure position should be open. To show this decision on the drawing, "fo" should be placed near the valve.***
- ***v200 provides heating to a closed chemical reactor; its failure position should be closed. To show this decision on the drawing, "fc" should be placed near the valve.***

Example A.6. Valve positioner: Valve 300 affects the flow out of the reactor. Experience has shown that the valve experiences some stiction, so that the valve position does not directly follow the air signal. The valve stem sticks until extra force overcomes static friction; then, the valve jumps to a new value and moves relatively freely for a short while. This leads to poor dynamic behavior; what should we do?

Stiction is common in control valves. It can lead to poor performance when

- ***the air pressure to overcome static friction is large***
- ***the control loop dynamics are slow***

A common manner for overcoming stiction is to install a valve positioner, which is a feedback controller on the valve itself. The valve positioner accepts the signal for the valve stem position as its set point, measurements the actual stem position, and adjusts its output, the air pressure to the actuator, to bring the measured stem position (near) to the desired value.

Example A.7. Valve Body: A food manufacturing process pumps a slurry and needs to regulate the flow rate using a control valve. Would the valve in Figure A.6 be appropriate?

Food processing requires hygienic conditions for its equipment and materials being processed. The process is periodically shutdown and cleaned using steam, hot water or caustic. Essentially all vestigial material must be removed during this cleaning. The valve in Figure A.6 has a globe body. Note that many crevices exist where slurry material could remain during cleaning; therefore, a globe valve is a poor choice for this application. Typically, a diaphragm valve with smooth surfaces would be used.

Example A.8. Valve range: Some processes experience very large variations in flow rate. For example, the process in Figure A.8a could experience its design rate with typical variations of ± 20% of design for long periods. However, when another unit in the plant is shutdown, the process could experience an increase in flow that is ten times the design rate. Is the design appropriate?

Typical design methods require that a control valve be sized to handle about 130% of its normal flow rate, thus, it is about 70% open under design conditions. These guidelines result in a valve (and pipe) that would be too small for the periodic, large flow rates occurring in the process. Therefore, the design in Figure A.8a is not appropriate.

We want precise adjustment of the control valve for the entire flow range, which would be challenging over a large range. Therefore, the process can be designed with two parallel valves, the larger having ten times the capacity of the smaller, as shown in Figure A.8b. The controller design to adjust two valves will be deferred to a later section in this chapter.

A.4 Signal Transmission

Most process control systems involve a structure of distributed equipment, with sensors and valves at the process equipment and the control calculations, many displays and data storage located in a remote, centralized facility. Therefore, values of key variables must be communicated between the sensors, calculations and valves (or other final elements). Recall that not all sensors and valves require signal transmission. Sensors with local displays and valves requiring manual operation have no signal to transmit. However, many (most) sensors and some valves require signal transmission, so that personnel in a single location can manage the entire process. Reliable, accurate and rapid signal transmission is essential for excellent process control.

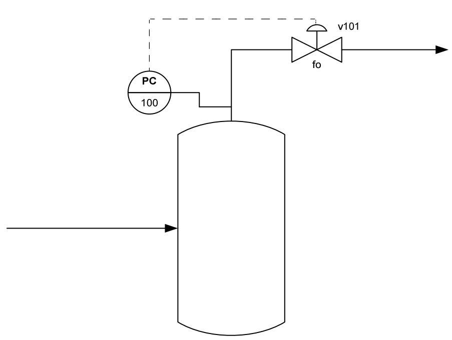


Figure A.8a. Pressure control using one pipe and valve.

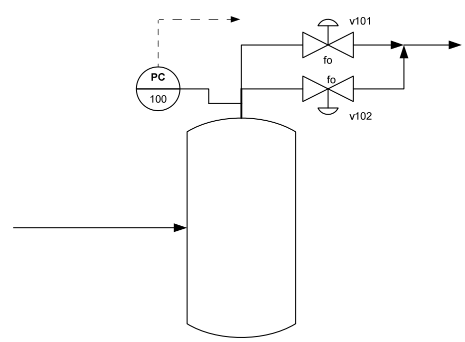


Figure A.8b. Pressure control using two pipes and valves.

Signal transmission is an integral part of every feedback control loop. Since "a chain is only as strong as its weakest link", excellence process control performance requires the signals to be transmitted between loop elements reliably, rapidly and accurately. To establish a basis for learning methods for signal transmission, we briefly review transmission issues in Table A.6. The relative importance of each item depends on the specific application. For example, fast response is required for controlling a mechanical system with rapid process dynamics, while high reliability is required for a safety-critical application.

Many methods for communication are in common use in society, e.g., radio, television, and cell phone transmissions. The following material is restricted to signal transmission for automatic control in the process industries.

Table A.6. Control signal transmission issues

Issue		Comment
• **Accuracy and reproducibility -** The signal transmission should be more accurate than the sensor and final element, so that no degradation results from the transmission. Here, accuracy means a difference in the signal value from its exact value.		Recall that the transmission occurs in the feedback loop, so that inaccuracy will affect the performance of feedback control. Field calibration must be possible without removing the equipment or compromising the safety protection.
• **Noise sensitivity -** The signal can be influenced by "noise", including electrical signals from other devices. The system must be designed to reduce the effects of noise.		
• **Reliability -** The failure of a signal transmission results in the loss of feedback control. For safety-critical signals, a backup (parallel) transmission path may be required.		Because the equipment may be located outdoors, it must be physically rugged and be resistant to water and significant changes in temperature. In a typical loop, the elements are connected in series. The reliability of a series of elements is the product of the reliabilities of each element. The power supplies are important potential sources of failures that can affect many signals simultaneously.
• **Dynamics -** Signal transmission is part of the feedback loop, and any delay degrades control. The transmission should be much faster than other elements in the loop.		Transmission by electronic analog or digital signal is much faster than the dynamics of a typical process element.
• **Distance -** In large plants, signals can be transmitted several thousand meters.		Physical connections have distance limitations. For very long distances, telemetry is used; however, reliability is sacrificed, so that this method is normally restricted to monitoring, with control implemented locally.
• **Interoperability -** We want to be able to use elements manufactured by different suppliers in the same control loop. For example, we want to use a sensor from supplier A, a controller from supplier B, and a valve from supplier C. To achieve		Standards are easily achieved for analog signals, 4-20 mA (electronic) and 3-15psig (pneumatic). At the present time, several competing standards exist for digital transmission.

this "interoperability", international standards must exist for the signals being transmitted between elements, i.e., sensors, controllers, and valves.		
• **Safety -** Naturally, the signal must not compromise the safe operation of the system. Since power is used for the transmission, special considerations are required to prevent combustion or explosion.		The power supplied must be low or the equipment must be contained within a controlled environment (enclosure). In addition, a high voltage or current caused by a circuit fault must not be transmitted to a process area where combustion could occur or where sensitive computing equipment could be damaged.
• **Diagnostics and configuration -** Ideally, the signal should be able to communicate several values, for example, • confirmation that the signal is being transmitted (live zero) • confirmation that the signal was received (echo) • configuration values required for sensors and final elements, e.g., sensor zero and span values.		Analog systems could provide many independent signals for every variable. However, this approach would be very costly because a separate cable would be required for each signal and is not done in practice. Digital transmission can communicate many values related to each variable.
• **Cost -** Typically, several transmission methods will satisfy basic requirements, so that benefits and costs must be evaluated to determine the best choice.		Remember that the total cost includes costs of installation, documentation, plant operations, and maintenance over the life of the sensor. See a reference on engineering economics to learn how to consider costs over time, using principles of the time value of money and profitability measures.

A.5 The conversion from analog to digital instrumentation

From the early applications of automatic control to the 1960's, control calculations, sensors, valves, and signal transmission in the process industries have relied on analog principles.

An analog computing system is a physical system that obeys physical laws yielding (nearly) the same equations as those equations to be computed, within acceptable

For an example, an analog system for adding numbers could add voltages representing the individual variables. The integral calculation in the PID controller can be performed by using an operational amplifier that integrates the input voltage. Analog computation is fast and reasonably accurate, but it is costly, needing dedicated hardware for each calculation, and inflexible, being inappropriate for complex calculations.

Beginning in the 1960's, control calculations have been converted to digital computation. At the same time, displays and historical data storage have been implemented using digital technology. In addition, complex calculations for process monitoring and optimization are performed using the digital control systems. In contrast, sensors, transmission and valves remained entirely analog until recently. Therefore, a brief review of this revolution in technology is presented here.

In the process industries, the following analog signals are in use.

- Physical position (connecting rod)
- Hydraulic pressure
- Pneumatic (air) pressure (3-15 psig)
- Electronic (4-20 mA DC)

Electronic analog instrumentation technology provides rapid response and introduces minimal inaccuracies, when compared with the responses of most chemical processes. However, analog instrumentation has limitations and deficiencies. Now that low cost and highly reliable technology is available, digital technology is being applied to sensors, transmission, and valves, so that every new sensor and valve can have a microprocessor! A comparison of analog and digital instrumentation functionalities is given in Table A.7. The reduced installation time and lower wiring cost indicate that the advantages of digital can be achieved without increased cost, and perhaps, with a savings.

In the traditional analog system, the sensor and valve are passive elements and all decision-making ability resides in the controller. In the digital system, key loop elements send and receive information and perform calculations in real time.

Thus, the Fieldbus includes a change from a "controller-centric" distributed digital control system (DCS) design to Field Control System (FCS), in which all key components are actively involved in computation and data storage.

Some of the more important features of elements in a Fieldbus system are introduced in the following.

1. **Configuration** - A large effort is required to configure (specify parameters like sensor range and valve characteristic) and verify data for elements of 100's to 1000's of loops. With Fieldbus, configuration can be prepared prior to plant construction and can be loaded and checked quickly. The savings in time and personnel costs can be substantial.
2. **Calculations** - Many calculations can be performed by the local processors to improve the performance of the elements.
    - Sensor nonlinearities can be corrected, e.g., thermocouple conversions from millivolt to temperature.
    - Several sensors can be combined to determine a more accurate value of a variable, e.g., density correction for a flow sensor.
    - A desired inherent valve characteristic can be programmed into a valve.
3. **Multidrop** - The fieldbus can connect many elements using the same cable, rather than using individual cables for each signal as required by analog transmission. Again, *savings can be substantial.*
4. **Two-way communication** - Any element can send and receive information, and any element can communicate with any other element on the fieldbus.

Table A.7. Typical communication and calculation for analog and digital control equipment.

Loop elements involved	Traditional, analog, also performed by digital	Enhanced, digital fieldbus
Sensor to controller	Signal representing the measured value sent to the controller	To controller • Measured value • Diagnostic from sensor to controller (e.g., drop in power, change in stream conditions) To sensor • Configuration of sensors (e.g., zero and span values) Calculations at sensor • Filtering measurement • Linearization • Correction for process environment (e.g., orifice for fluid temperature and pressure) which can require the use of several sensors
Controller to valve	Output of controller calculation sent to the valve (i/p converter)	To valve (to the i/p converter) • Output of controller • Configuration of valve (max/min openings, characteristic, etc.) To controller • position of stem position of valve • diagnostic from valve to controller (e.g., stiction, loss of air pressure) Calculations at valve • Modification of relationship between control signal and stem position to modify characteristic

The distributed computing available in fieldbus makes possible the distribution of the controller calculations. For example, the element performing the controller (e.g., PID) calculation could be physically located at the sensor or valve. However, most plants desire control information to be available at a centralized location, the control room; therefore, the controllers are usually located in this control room.

In fieldbus designs, all elements (sensor, controller and final element) exchange information via digital transmission. We desire to purchase the best elements available from different suppliers.

Therefore, international standards are essential to ensure equipment from different suppliers will function in a network; this is termed interoperability.

Industry began to develop these standards in 1985, initial fieldbus systems were placed in operation in the 1990's, and standards and systems continue to evolve.

What will you experience when you work in process plants? Unlike office applications, where old calculation equipment is discarded and replaced frequently, replacing instrumentation is costly.

Because legacy instrumentation has a very long life, you will likely see a mixture of technologies, some state-of-the-art and some 20-30 years old!

The next step in the digital revolution is wireless transmission, which will further reduce the cost of installation. We are all familiar with wireless through use of cell phones, and we have experienced periodic loss or interruption of a call. Clearly, wireless transmission for control of chemical processes must have a very high reliability, so that the technology is being applied slowly as systems meeting reliability demands become available.

A.6 Conclusions

The material in this appendix has been chosen to provide a basis for the analysis of process control, safety, reliability, and monitoring and troubleshooting. The engineer needs to understand these basics to design and to operate complex processes. Naturally, the coverage has emphasized issues to be considered and shown examples of application of these issues. The reader will investigate the issues for their process technology (chemicals, pharmaceuticals, pulp and paper, minerals, fuels, etc.) and access information from equipment suppliers.

Additional Learning Topics

Understanding accuracy and the sources of inaccuracy are important when dealing with all process measurements. The following provide insights useful for practicing engineers and scientists.

Site provided by NIST (National Institute for Science and Technology)
http://physics.nist.gov/cuu/Uncertainty/index.html

Wheeler, Anthony and Ahmad Ganji (2004) Introduction to Engineering Experimentation, Prentice Hall, Upper Saddle River, (ISBN: 0-13-065844-8), see Chapter 2
ftp://ftp.prenhall.com/pub/esm/sample_chapters/engineering_computer_science/wheeler/index.html

The basic measurements for the process industries are P, T, F, and L. Tutorial information on sensors for these variables is given in the following.

For pressure, flow and level sensors, The Omega Internet site for pressure, flow and level (select the appropriate link, http://www.omega.com/literature/transactions/
For temperature sensors, http://www.omega.com/pdf/temperature/Z/pdf/z021-032.pdf

For an **outstanding** public-domain reference on instrumentation, see the following.

Kuphalt, T (2012) Lessons in Industrial Instrumentation,
http://www.openbookproject.net/books/socratic/sinst/

Valve bodies must be matched to the process fluids and needs. An introduction to the common valve bodies is given in the following.

The Spirax Sarco site for boiler and steam systems.
http://www.spiraxsarco.com/resources/steam-engineering-tutorials/control-hardware-el-pn-actuation/control-valves.asp

P&IDs (piping and instrumentations drawings) are important for documenting the process and control design. The following provides a nice overview of a range of drawings used in chemical engineering and details on the P&ID.

Turton, Richard, Richard Bailie, Wallace Whiting, Joseph Shaiwitz (2003) Analysis, Synthesis, and Design of Chemical Processes, Prentice-Hall, Upper Saddle River, See sample chapter at
http://www.pearson.ch/download/media/9780130647924.pdf

Digital control calculations have been in industrial practice for many decades. The transition to digital instrumentation (a microprocessor in each sensor and valve) continues.

Portal for white papers on Digital instrumentation and transmission is given at
http://us.profibus.com/resources.aspx?pagetype=white_papers

An introduction to concepts of fieldbus is given at
http://www.science.upm.ro/~traian/web_curs/Scada/docum/fieldbus.pdf

References

Beychok (2012) released through creative commons, (**Thanks!**),
http://en.citizendium.org/wiki/File:Control_Valve.png

Cornish, Derek (1995) “Instrument Performance”, Measurement and Control, 27, 323-328.

Liptak, Bela (1999) Instrument Engineer’s Handbook, 3rd Edition, Process Control, CRC Press, Boca Raton

Liptak, Bela (2003) Instrument Engineer’s Handbook, 4th Edition, Process Measurement and Analysis, Volume I, CRC Press, Boca Raton

Marlin, Thomas (2000) Process Control: Designing Processes and Control Systems for Dynamic Performance, McGraw-Hill, New York.

Marlin, Thomas (2012) PC-Education Internet site, http://www.pc-education.mcmaster.ca/

Microsoft (2012) Visio™, http://office.microsoft.com/en-us/visio/

Turton, Richard, Richard Bailie, Wallace Whiting, Joseph Shaiwitz (2003) Analysis, Synthesis, and Design of Chemical Processes, Prentice-Hall, Upper Saddle River